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Age Dependent Cost-Effectiveness of Cochlear Implantation in Adults. Is There an Age Related Cut-off?

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Conclusions: Performing both sequential and unilateral CI is cost-effective up to very advanced ages when compared with hearing aids. **Key Words:** Adults—Age—Cochlear implant—Cost—Cost-effectiveness—Cost-utility—Discount—Effectiveness—Implantation—Markov—Quality adjusted life year—Quality—Related—Sensitivity—Utility.

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The worldwide number of patients who underwent cochlear implantation (CI) has increased constantly over the past decades. Reports have indicated that 25,000 patients had cochlear implants by 1998 (1) and this increased to 324,200 by 2012 (2). According to cochlear implant manufacturers, the number of implanted patients may have reached 500,000 in 2017 and is likely to continue to grow rapidly. According to the World Health Organization (WHO, www.who.int), approximately 11.7 million people worldwide suffer from profound hearing loss. Sequential CI and implantation in the elderly is becoming routine practice in many countries. In addition, implantation for unilateral deafness or tinnitus is already standard in several countries (e.g., Germany) and is likely to increase the indication for implantation worldwide (3,4). The total cost of a CI includes the preoperative evaluation, the implanted device itself, the surgery with the attendant hospitalization, and the postoperative rehabilitation. The first CI with a commercialized multi-electrode device was performed 40 years ago (5), but the continuous technical improvements and the need for comprehensive pre- and postoperative care have generally kept the costs high. Since the recovery of lost hearing is associated with an immense gain in the quality of life (QoL), CI has been shown to be cost-effective for many different situations in both pediatric and adult populations (6,7).

Nevertheless, limited economic resources, longevity, and recently developed expensive therapeutic options in various medical fields have caused a rise in health related cost-effectiveness discussions. The quality adjusted life year (QALY) quantifies the benefits of an intervention as a function of QoL and time duration. The incremental cost-effectiveness ratio (ICER) describes the difference in costs of two different interventions in relation to the achieved benefit by the better intervention (in costs per QALY gained). Therefore, it allows a comparison of two different interventions considering both costs and gain in QoL. Costs are measured in monetary units, the gain is

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measured in QALY. For example, if a more expensive therapy brings a gain of 0.5 QALY, but costs 10,000 USD more, then the ICER of this more expensive therapy in comparison to the less expensive therapy would be 20,000 USD/QALY. The exact formula is presented in the methods section. There is an ongoing debate on what is a reasonable allowable cost of a gained QALY. The commonly applied ICER threshold is $50,000, but recently a shift to higher numbers ($100,000, $150,000, $200,000, and $300,000) are discussed and often recommended (8).

From a medical point of view, CI in the elderly is highly effective (9). However, as the QALY is directly influenced by the duration of the achieved benefit, the calculated cost-effectiveness depends on the remaining life expectancy. While for unilateral CI such calculations might seem ethically questionable, the evaluation of the cost-effectiveness of bilateral CI in the elderly population in the context of increasing medical costs and limited economic resources seems reasonable.

At first glance, cost-effectiveness considerations are primarily political, economic, and ethical questions. Nonetheless, from a physician's view, they allow standardized comparisons of different therapies and procedures, across from different specialties.

The goal of this cost-utility analysis was to analyze the cost structures and the cost-effectiveness of CI in a ''high income country,'' as defined by the WHO, with a focus on age and sex for both unilateral (UNI) and sequential (SEQ) CI.

PATIENTS AND METHODS

As in previous studies on cost-effectiveness of CI (7), reporting of methods and results are guided by the Consolidated Health Economic Evaluation Reporting Standards (10).

Setting

The target population were adults with severe to profound postlingual hearing loss. Qualification criteria for CI are listed in the national guidelines for CI and follow-up care (11). These guidelines require that spoken language cannot be sufficiently understood with a fitted hearing aid (HA) and that the patient exhibit anatomical conditions that allow for implantation.

Cost parameters were collected for the year 2017 in a public tertiary referral hospital setting in Switzerland. The country population in 2016 is estimated 8.4 million. Life expectancy is 81 years for men and 85 years for women. In 2016, 234 CI were performed in five national centers (four of them university hospitals). Since the first implantations in 1977, by 2016 a total of 3,096 patients were implanted (12).

Patient Cohort for Comparison

For a better comparison of published data in literature, an own patient cohort in the Swiss setting was analyzed retrospectively for their mean age, device failure rate, and non-user rate. Included were 100 adult patients, who received their first implant and were implanted consecutively between 2010 and 2013, allowing for a follow-up rate of 5 years.

Costs

Detailed costs, timing, number of visits, and the type of the different examinations are listed in Table 1. Mandatory health insurance and social security covers most of the costs. A small co-pay is paid by the patient. Prices are set on a national level by the Swiss health care system. The hospitalization and operation costs are reimbursed by the insurance on a flat rate base. This flat rate includes the hospitalization, the implantation, the implant, and the overhead costs. The number and types of visits are standardized at the authors' institution. Table 2 shows the recurring costs of HA and cochlear implant, as well as the corresponding device replacement intervals (''time frame''). For illustration, the ''yearly average'' costs are shown as well. For the evaluation of the model, the original values with the associated intervals were used (10 years for CI and 6 years for HA). For the HA, a reimbursement rate of 6,140 CHF was used for the calculations. Formally, this is the amount for HA, which was available to all hearing impaired patients every 6 years until 2011 in our system. Since then, the general amount has declined to 1,650 CHF every 6 years. Patients with a severe to profound bilateral hearing loss, as in our study population, qualify for a ''hardship case,'' which warrants full coverage. On average this corresponds to the amount of 6,140 CHF every 6 years.

The HA situation reflects the bilateral HA status. As we analyze the situation for patients with bilateral severe to profound hearing loss, it is assumed that the costs for HA no longer apply once a CI is successfully implanted. If a patient benefits from a HA on the contralateral side after UNI, the implantation of the second side would be offered. As HA are reimbursed every 6 years, it is assumed that the patients would use the HA they already possess in the meantime. However, a generous use of HA, even with little benefit, is advocated. Some patients will continue to use a HA after UNI continuously and the effect of the additional HA costs for this situation is analyzed in a separate sensitivity analysis.

In case of device failure and reimplantation, a different flat rate value of 15,866 CHF is used. This represents the costs billed by the hospital, with the new implant covered by the manufacturer. Details on the time frames and failure rates are mentioned in the next section.

Only direct costs like preoperative evaluation, MRI, audiology tests, hospitalization, rehabilitation, and device replacement costs were used for calculations. Current discount rates published by the Swiss National Bank are 0%. To allow comparison of the results with other studies and places, the calculations were repeated using various discount rates (0, 1, 3, and 5%). At the time of writing, the currency exchange rate of CHF to USD was 1 CHF to 1.01 USD.

Probabilities, Health Utilities, and Replacement Costs

Reported device failure rates vary and have been reported ranging from 1.84% (13) to 3.4% (14), 4.8% (15), and 5.1% (16). In case of device failure, Bhatt et al. (16) describe a mean duration from implantation to device failure of 1.9 years with a range from 0.04 to 6 years. In the basic model, it is assumed, that the manufacturer would provide the new device (10-year manufacturer warranty in our system). In the sensitivity analysis section (Results), we relax this assumption. In our own patient cohort, we found a device failure rate of 2%. For the calculations, a value of 3.4% was used (the mean of the five mentioned values).

Summerfield and Marshall (17) report a non-user rate of 2% after 6 months with a plateau of 6% after 4 to 7 years. In our cohort, 4% were non-users after 5 years, comparable to the

TABLE 1. *One time costs*

		Time Point (in days)	HA	UNI	SEQ
1.	HA costs				
	HA initial costs	–	6,140	-	-
2.	First CI costs				
	Initial specialist consultation	0	–	338	–
	Audiology assessment	0	–	398	–
	Subsequent specialist consultation	7	–	275	–
	MRI	83	–	710	–
	Subsequent specialist consultation (surgeon)	97	–	98	–
	Implantation (hospitalization, implantation, implant, overhead costs)	157	–	30,866	–
	General practitioner consultation (removal of stitches)	164	–	44	–
	1st fitting of sound processor	185	–	517	–
	Sound processor	185	–	12,349	–
	2nd fitting of sound processor	192	–	391	–
	3rd fitting of sound processor	213	–	391	–
	Audiology assessment 1	241	–	729	–
	Audiology assessment 2	325	–	729	–
	Audiology assessment 3	409	–	729	–
	Weekly training with speech therapist	Up to 365	–	2,520	–
3.	Second CI costs				
	Initial specialist consultation	0	–	–	338
	Audiology assessment	0	–	–	398
	Subsequent specialist consultation	7	–	–	275
	Subsequent specialist consultation (surgeon)	97	–	–	98
	Implantation (hospitalization, implantation, implant, overhead costs)	157	–	–	30,866
	General practitioner consultation (removal of stitches)	164	–	–	44
	1st fitting of sound processor	185	–	–	517
	Sound processor	185	–	–	12,349
	2nd fitting of sound processor	192	–	–	391
	3rd fitting of sound processor	213	–	–	391
	Audiology assessment 1	241	–	–	729
	Audiology assessment 2	325	–	–	729
	Audiology assessment 3	409	–	–	729
	Weekly training with speech therapist	Up to 365	–	–	2,520
	Total incremental costs	UNI versus HA	–	51,084	–
		SEQ versus UNI	–	–	50,374

HA indicates hearing aids; SEQ, sequential cochlear implantation; time point (in days), gives an idea on the time course of CI with the average intervals between the different examinations; UNI, unilateral cochlear implantation.

4.7% reported by Bhatt et al. (16). Other studies reported 1.1% (18) and 2.78% (19).

For calculations, we used a mean probability rate of 3.7% for non-users. For our analysis, the device failure and non-user probabilities were applied both after 2 years and 1 year, respectively. This was in accordance with our clinical observations, where device failure and non-users are identified to be within these intervals. Additionally, a sensitivity analysis for different device failure and non-users rates was performed.

In a large review, Crowson et al. (6) evaluated health utility values and calculated weighted-average QoL gains for both generic and diseases specific QoL measures from published data up to 2017. Their weighted averages for disease specific measures were used in our calculations and are listed in Table 3. In summary, these health utilities values represent the change in the QoL achieved by the intervention and are based on questionnaire results (e.g., Health Utility Index-Mark 3 (20), Nijmegen Cochlear Implant Questionnaire NCIQ (21), and others).

Analysis

Adults with bilateral HA, unilateral CI, and bilateral CI were compared in an adapted Markov model (22). A Markov model is typically used to predict the future behavior of a complex system (sometimes illustrated with a decision tree), based on actual known probabilities. A mathematically strict Markov model assumes that the probabilities applied are the same for each step (year). In our model, age related mortality and the interventions create different probabilities. Also, instead of using averaged yearly costs, the model took into account the real costs and time intervals (e.g., HA replacement costs of 6,140 CHF every 6 yrs).

Figure 1 shows the decision tree with decision nodes (squares) and event nodes (circles). The probabilities mentioned above are applied at each of the event nodes. Bilateral CI option actually represents the sequential implantation. In the author's institution, simultaneous bilateral implantation is routine practice in pediatric cases only. Eventually, all of the patients end up in one of the following final states: HA, UNI, SEQ.

TABLE 2. *Recurring costs*

		Time Frame	HA	UNI	SEQ
1.	HA				
	Batteries	Yearly	60	–	–
	Replacement costs	Every 6 years	6,140	–	–
	Specialist consultation	Every 2 years	339	–	–
2.	CI				
	Batteries	Yearly	–	400	800
	Sound processor	Every 10 years	–	12,349	24,698
	Follow–up fitting	Yearly	–	391	391
	Audiology follow-up assessment	Every 2 years	–	365	365
	Yearly average		1,253	2,208	3,843

HA indicates hearing aids; SEQ, sequential cochlear implantation; UNI, unilateral cochlear implantation.

The yearly all-cause mortality, with slight differences for men and women, was extracted from Swiss life tables from the Swiss Federal Statistical Office (23). The time unit used for analysis was 1 year. Since the utility scores that were used were collected from adult populations, the analyses start at age 18.

To compare different interventions, four values were calculated in a first step: the cost of intervention 1 (C_1), the cost intervention 2 (C_2), the health utility value of intervention 1 (H_1), and the health utility value of intervention 2 (H_2). The costs are in CHF, the health values in QALY. The ICER was then calculated according to the formula $\text{ICER} = (C_2 - C_1)/(H_2 - H_1)$, resulting in a value that represents the incremental cost per QALY (in CHF/QALY). The ICER was calculated for each combination of age (18–110 yrs) and sex. The time horizons are age and sex dependent and represent the individuals remaining life expectancy. All the costs and health utility values were calculated over the expected patient's lifetime.

In summary, the incurring costs for each decision (of the decision tree) were applied in a year-by-year calculation, with continuously adapting the age dependent mortality rate.

As the resulting ICERs are age dependent, they were plotted as curves (Fig. 2). To further characterize these curves, a ''trend point'' was calculated. This point describes the age, at which the steepness of the curve increases by 1,000 CHF per year.

RESULTS

General Costs

HA start with one-time costs of 6,140 CHF which is incurred again after each 6-year period. In addition, batteries and specialist consultations, add an average yearly costs of 1,253 CHF. The cost for unilateral CI was found to be 51,084 CHF and a second, sequential bilateral CI, was 50,749 CHF. In addition, the average yearly costs were 2,208 and 3,843 CHF, respectively (Tables 1 and 2).

Incremental Costs and Outcomes

Figure 2 shows the ICER as a function of age at intervention. The younger a patient is at implantation, the longer he or she will enjoy an improved QoL. This makes the intervention more cost-effective. The highlighted horizontal 50,000 and 100,000 CHF lines represent a conservative (50,000) and a more contemporary (100,000) cost-effectiveness threshold. Precise costs per QALY gained for different ages are shown in Table 3 (right half). For example, when a 20-year-old woman upgrades from HA to UNI, her ICER (the cost of the gained benefit) is 6,261 CHF per QALY. When an 80-year-old woman upgrades from HA to UNI, her ICER is 22,124 CHF, as her remaining life expectancy is shorter. Table 4 shows three characteristic ages: 1) the age at which the 50,000 CHF threshold is crossed, 2) the age at which the 100,000 CHF threshold is crossed, and 3) the ''trend point,'' (as defined above) which is illustrated in Figure 2. With a threshold of 50,000 CHF, performing unilateral CI in comparison to HA is cost-effective up to an age of 91 for women and 89 for men. Sequential CI in comparison to HA is cost-effective up to an age of 87 for women and 85 for men. Sequential CI in comparison to unilateral CI is cost-effective up to an age of 80 for women and 78 for men, when the more contemporary threshold of 100,000 CHF per QALY is applied.

TABLE 3. *Costs per QALY for life time horizon at different implantation ages*

Treatment Group	One Time Costs (Incremental)	Yearly Costs (Incremental)	Health Values (Incremental)	20 y (f)	20 y (m)	40 y (f)	40 y (m)	60 y (f)	60 y (m)	80 y (f)	80 y (m)
UNI versus HA	51,084	955	0.28	6,261	6,459	7,499	7,891	10,425	11,461	22,124	25,745
SEQ versus HA	101,459	2,590	0.38	10,818	11,111	12,652	13,234	17,020	18,528	33,974	38,233
SEQ versus UNI	50,374	1,635	0.1	25,101	25,730	29,345	30,710	40,371	44,323	97,810	114,408

Shown are incremental costs and incremental health values in the first three rows. The right eight rows show different age and sex combinations and the incremental costs for 1 QALY gained (in CHF/QALY) for the different situations. HA indicates hearing aids; SEQ, sequential cochlear implantation; UNI, unilateral cochlear implantation.

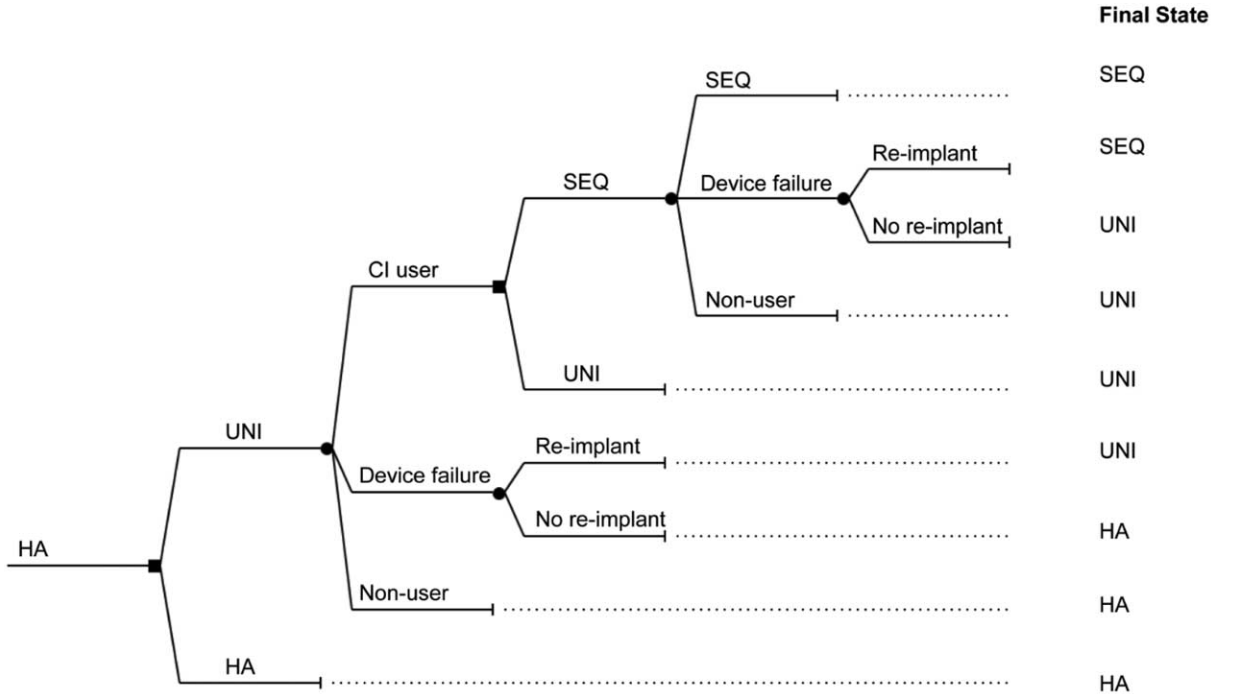

FIG. 1. Decision tree. Squares represent decisions. Circles represent events. The probabilities are applied at the forks of the event nodes.

Table 4 shows also the effect that applying a discount rate of 1, 3, or 5% has on the age at which a threshold line is crossed. The ICER of unilateral CI in comparison to hearing aids is 6,261 CHF for a 20-year-old woman, 7,499 CHF for a 40-year-old woman, 10,425 CHF for a 60-year-old woman, and 22,124 CHF for an 80-year-old woman.

Sensitivity Analysis

Some of the uncertainties inherent in such a model are addressed by a sensitivity analysis. Parameter changes were made in the discount factor (shown above, Table 4), non-user rate, device failure rate, and device failure coverage.

When the lowest device failure rates and non-user rates found in literature were applied (1.84 and 1.1%, respectively), the age at which the 50,000 CHF threshold is crossed, changes by a maximum of 1 year as compared with the original calculation. For example, in the UNI versus HA situation in women, the point where the curve crosses the 50,000 CHF threshold line moved from 91 years to 92. When the highest rates reported in literature were used (5.1 and 6%, respectively), the maximum change was also 1 year (SEQ versus HA in men, change from 85 to 84 yrs). These effects seem to be marginal.

As discussed further above, the cost of reimplantation was 15,866 CHF under the assumption that the device

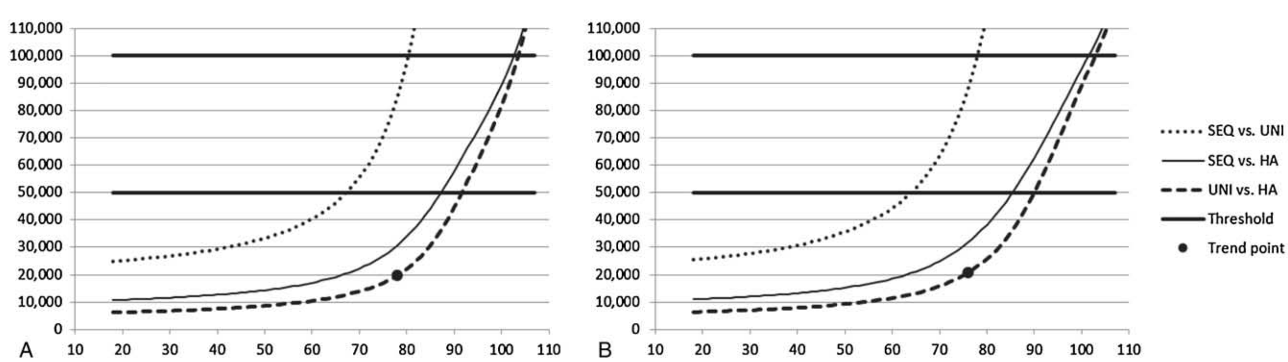

FIG. 2. ICER curves. *Y*-axis shows the ICER (the cost of one QALY gained) in dependence of age at intervention (*x*-axis) for women (*A*) and men (*B*). The highlighted horizontal lines show the cost-effectiveness thresholds (the conservative threshold at 50,000 CHF and the more contemporary thershold at 100,000 CHF). In the UNI versus HA curve, the "trend point" is shown for illustration. HA indicates hearing aids; ICER, incremental cost-effectiveness ratio; QALY, quality adjusted life year; UNI, unilateral.

TABLE 4. *Specific results*

Treatment Group	Comparison	Gender	Age at 50,000/QALY	Age at 100,000/QALY	Age at ''trend point''
UNI	Versus HA	F	91 (92/92/93)	103 (103/104/104)	78
		M	89 (90/91/91)	102 (103/103/103)	76
SEQ	Versus HA	F	87 (88/89/90)	102 (102/103/103)	74
		M	85 (86/87/89)	101 (101/102/103)	72
	Versus UNI	F	67 (69/72/74)	80 (81/82/83)	62
		M	64 (66/69/71)	78 (78/80/81)	58

Shown are the specific ages when the thresholds are crossed and the age at the ''trend point.'' The values in parenthesizes show the age if a discount factor is applied (1, 3, 5%). For example, if a discount rate of 5% is applied in the calculations, the age at which the 50,000 CHF threshold is crossed for women (UNI versus HA), changes from 91 to 93 years.

HA indicates hearing aids; SEQ, sequential cochlear implantation; UNI, unilateral cochlear implantation.

was covered by manufacturer warranty or that the patient did not require a new implant (electrode displacement etc.). In some revisions however, the CI needs to be replaced and is not covered by the manufacturer's warranty, resulting in costs of 30,866 CHF. To address this uncertainty, different device failure coverage averages were used for the calculation, but showed only a marginal effect. The only noticeable change was observed in the SEQ versus UNI situation in men, when a 0% manufacturer coverage was applied. The age, at which the 50,000 CHF threshold is crossed, moved from 64 to 63 years.

If a unilaterally implanted patient continues to use a HA on the contralateral side (additional costs of 3,000 CHF every 6 yrs), the cost-effectiveness slightly changes, for both, the UNI versus HA situation and the SEQ versus UNI situation. The age at 50,000/QALY (Table 4) changes as follows: UNI versus HA from 91/89 (f/m) to 89/86; SEQ versus UNI from 67/64 (f/m) to 70/66.

DISCUSSION

In contrast to other studies on cost-effectiveness for CI or other medical interventions in general, our model specifically targets the effect of the age at the time of intervention. The ICERs are therefore different for each individual age. All the other studies looked at the target population as a whole.

To compare our results with the results of the other studies, we calculated the average age of our own CI patient cohort (51 yrs). In our model, the ICER for the UNI versus HA situation is 8,746 CHF for a 51-year-old woman and 9,393 CHF for a 51-year-old man. This compares to an ICER of 9,799 AUD (equivalent to 7,313 CHF) found by Foteff et al. (7) in an Australian setting and Chen et al. (24), who found an ICER of 9,426 $CAN (equivalent to 6,993 CHF) in a Canadian population. In another study in the UK (25), an ICER of 14,163 pounds (equivalent to 18,884 CHF) was found. Overall, these numbers from 2014 to 2017 from different countries and systems are similar, while the UK (2009) is an outlier.

To compare our results in the SEQ versus HA situation, an ICER of 14,506 CHF for a 51-year-old woman and 15,463 CHF for a 51-year-old man were calculated in our population. These numbers can be compared with the 14,658 $CAN (equivalent to 10,882 CHF) published by Chen et al. (24).

For the SEQ versus UNI situation, our ICER was 33,854 CHF for a 51-year-old woman and 36,219 CHF for a 51-year-old man. In the Canadian population it was 55,020 $CAN (equivalent to 40,846 CHF) and 26,765 AUD (equivalent to 19,870 CHF) in the Australian population. One reason for this variance is that the Australian value describes simultaneous CI in comparison to HA. Apart from that, health utility values for the SEQ versus UNI situation are difficult to measure and vary in literature.

The health utility measures for the UNI versus HA situation are better studied and similar values are used in different publications. Differences in costs between our population and the costs of other countries in the UNI versus HA situation may reflect the cost structures in the different countries. The gross domestic product at purchasing power parity per capita (GDP PPP PC), defined by the International Monetary Fund (www.imf.org), describes the gross domestic product in relation to the population number and the standardized ''international dollar.'' The GDP PPP PC is 61,360, 48,141, 49,882, and 43,620$ for Switzerland, Canada, Australia, and the UK respectively (the USA as comparison is 59,495$). Population characteristics of Switzerland, Canada, Australia, and the UK are also comparable. Life expectancy, the main parameter on which our model is based, is practically the same. For men/women it is 81/85, 81/85, 81/85, and 80/83 years respectively (in the USA 76/81 yrs) (www.who.int). The population sizes are different (8.4 mil, 36.7 mil, 24.6 mil, and 66.0 mil, respectively; 325.7 mil in the USA as a comparison), but does not affect our model.

Figure 2 shows the most relevant information as it summarizes graphically the ICER values for each age and sex combination in relation to different interventions and thresholds: compared with HA, performing a UNI or SEQ is cost-effective up to very advanced ages for both threshold values (50,000 CHF and 100,000 CHF). When a 100,000 CHF threshold is used, the analysis indicates that SEQ compared with UNI is also cost-effective up to an age of 80 years for women and

78 for men. The shape of the curves can be divided by what was defined as a ''trend point'' into a flat and a steep portion. The flat section depicts the age range in which the intervention is exceptionally cost-effective. That is, a unilaterally implanted woman before age 78 would be ''highly cost-effective'' but the procedure remains cost-effective until age 91 (and even until age 103 if the 100,000 threshold is used). Our results also indicate that SEQ is highly cost-effective as compared with HA regardless of age. The results are less favorable when comparing SEQ to UNI. The effect of the second implant in relation to the first implant is, due to the immense effect of the first implant, smaller. The effect of the second implant is harder to measure in questionnaires and less published data are available (6). Nevertheless, with contemporary threshold values (8), our results also allow for SEQ up to highly advanced ages.

In summary, cost and age are practically no reason to argue against CI in an otherwise suitable patient.

Limitations of the presented study are the health utility values, which are taken from literature (6) and represent values for an average study population. One might argue, that the health utilities scores change for each age category and that an elderly population might have less benefit and therefore the implantation at high age is less cost-effective. Although we did not assess health utility values for older populations, the impact on hearing loss in the elderly, especially in combination with depression and dementia, is well known (26). A robust clinical effectiveness of CI in the elderly was shown by Rohloff et al. (9). We, therefore, assume that our results with respect to the elderly are reasonable.

However, more research on utility values for different groups and indications (e.g., single sided deafness) and age categories would be of great interest for future studies on cost-effectiveness of CI.

Generally, the limitations of a mathematical model are that certain assumptions are required. These assumptions were made in accordance with our clinical experience. Additionally, our assumptions were tested with a sensitivity analysis, which showed only very small changes in the results. Still, there are assumptions that remain debatable. For example, it is questionable if all patients use the available 6,140 CHF to replace their HA every 6 years. Some might choose to go for longer intervals, even though there are no out of pocket costs associated with the 6-year interval.

Finally, ICERs allow comparisons of the cost-effectiveness of interventions from different medical fields. Studies have shown ICERs of 88,903$/QALY for total knee replacement (27) and 5,629$/QALY for laser photocoagulation for age-related macular degeneration (28). Bae and Mullins (29) reviewed 54 articles and found a mean ICER of $138,582/QALY for cancer-specific drug interventions.

These values can put the ICER of sequential CI into a broader context.

CONCLUSION

Sequential and unilateral CI is highly cost-effective when compared with hearing aids.

When compared with unilateral CI, sequential CI is cost-effective up to around 80 years when a threshold value of 100,000 CHF is applied.

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